Field Measurements of the Influence of Bubbles on the Inherent Optical Properties of the Upper Ocean.

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LONG-TERM GOALS

The long term goals of this project are to better understand the influence of air-sea interaction processes on hyperspectral remote-sensing of the ocean's surface.

OBJECTIVES

This research program is concerned with understanding the role of bubbles injected by breaking waves in modifying the inherent optical properties (IOPs) of the upper ocean. Surface-layer oceanographic phenomena such as turbulent mixing and Langmuir cells are also addressed in the investigation as they are known to play a large role in determining the depth to which bubble clouds penetrate, the bubble residence times, and the bubble size distributions. The resulting data collected will provide the necessary information for the development of physical models for the evolution of bubbles in the surface wave layer based on wind and wave forcing. Models of remote sensing reflectance will be extended from these synoptically forced bubble models to understand the role of bubbles in modifying the optical properties of the upper ocean. A byproduct of the research will be models to correct for bubble mediated effects in hyperspectral imagery such as the Coastal Ocean Imaging Spectrometer (COIS) using wind and wave information available through other remote sensors such as microwave scatterometers and synthetic aperture radar. The program also presents the opportunity to develop techniques for inverting remotely-sensed hyperspectral imagery for in-situ bubble concentrations.

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APPROACH

As part of the Hyperspectral Coupled Ocean Dynamics Experiment (HYCODE), a field sampling program was designed for measurements of bubbles and IOPs over a range of sea states. The variability of the bubble field that results from wave breaking necessitates that the bubble and optical field be sampled with sufficient temporal and spatial resolution. Acoustic techniques that have been refined over the last decade (Terrill & Melville, 2000) are used for measuring the bubbles in conjunction with optical measurements to directly measure the bubble field and the resulting optical scattering.

WORK COMPLETED

This project is in its third year of a five year program. Details relating to accomplishments in years 1 and 2 of the program have been summarized in earlier reports. These include:

- Laboratory studies of the nature of underwater light scatter from bubble assemblages resulting from breaking waves.

- Development of novel instrumentation for HYCODE field effort # 1.

- Execution of field studies at the LEO -15 site off the coast of Tuckerton, New Jersey. Equipment deployed included a surface buoy developed for air-sea interaction measurements and included sensors for the measurement of optical attenuation, bubble populations, waves, and meteorological quantities. Also deployed was a 26' aluminum research vessel outfitted with a bow-mounted spar which extended 2m below the water's surface. The spar was equipped with sensors for the measurement of bubbles, optical attenuation, turbulence, waves, and water temperature. Differential GPS onboard the vessel allowed the measurement of the spatial scales of the various parameters.

As a result of the relatively benign sea conditions and turbid water present in New Jersey during the 2000 field campaign, an alternate field experiment site was chosen for our group's efforts in 2001. Given our need for a location with optically clear water and higher sea states, we made plans for joining a separate ONR field experiment which would be using the research platform FLIP off the coast of Oahu, HI in the August-September 2001 time frame. While the objectives of the Rough Evaporation Duct (RED) experiment were to examine near-surface atmospheric EM and EO propagation, there was significant synergy between our group's efforts and the other scientists. These interests include the interplay between our efforts in understanding the relationship between wave breaking, bubble generation, and their impact on the underwater light fields and the RED group's efforts in measuring aerosols in the marine boundary layer. As a result of this interaction, we expect we can further the present understanding of atmospheric corrections that are currently used in hyperspectral imagery and separate the effects of air-sea effects (eg. bubbles and waves) and atmospheric aerosol concentrations. Figures 1 and 2 provide an overview of the instrumentation deployed in HI as part of our HYCODE effort.

PRELIMINARY RESULTS

Scattering calculations based on bubble size distributions measured in the field indicate that optical scattering resulting from active breaking waves is relatively spectrally flat, with the dominant bubble

sizes contributing to optical scattering being 50-100 microns in size. Results from laboratory measurements were found to be consistent with these findings. Calculations also predict an enhancement in the remote-sensing reflectance in the blue-green region when bubbles are present in significant quantities. This enhancement will depend on the relative concentrations of the other water-borne optical constituents present. Prior to detailed radiative transfer modeling, phase functions of representative bubble populations measured in the field were examined. As a result of this exercise, we have determined that light is scattered in the forward direction much more significantly than other optical constituents typically found in the ocean, implying that phase functions specific to bubble populations must be used when bubbles are included in radiative transfer calculations. A summary of bubble phase function relationships are summarized in figure 3.

We also studied the effect of a three-dimensional bubble cloud on remote-sensing reflectance (RSR). A 3-D Monte Carlo code was used to study this effect as a function of light wavelength and chlorophyll concentration in water. Our results show that even small bubble clouds produce water leaving-radiances that are significant even in the near infrared spectral region. This has an impact on remote sensing algorithms, which generally assume that water-leaving radiance in the near infrared is completely negligible. An example of the spectral RSR across a bubble cloud is shown in Figure 4. Further studies are underway to examine the effects of the size and concentration of bubble cloud and 3-D edge effects.

As a result of our field efforts, we have the first known data sets concerning the impact of bubble populations that result from wave breaking and their influence on upper ocean optical properties. This data set is complemented by the extensive supporting measurements of the wind and wave conditions which will aid in the interpretation of the data. Data collected from the two different sites will allow us to compare results from the Case 1 vs. Case 2 conditions.

IMPACT/APPLICATIONS

The discrimination between Case 1 and Case 2 waters loses its meaning if we recognize that the scattering properties of near-surface waters can be largely determined by gas bubbles whose concentration and size distribution (i.e. major determinants of optical scattering) vary greatly in time and space as a function of wind and wave conditions. Consequently, one can argue that even Case 1 waters, do not exist in the top few meters of the ocean which are the most important for remote sensing of ocean color. Part of the error in the data products generated by the existing ocean color algorithms can certainly be attributed to variable concentration of gas bubbles submerged in the near surface layers. As an example, the existing parameterizations of backscattering coefficient in the semi-analytical algorithms for inverting reflectance measurements will most likely be biased by the presence of the sea state dependent bubble backscatter. In addition, submerged bubbles can influence the validation of the atmospheric correction, which is based on the comparison of in situ and satellite-derived water-leaving radiances. The quantification of these errors at the present time is, however, impossible because no simultaneous data exist that characterize optical properties and bubble populations in the water. It is anticipated that results of this research will provide an indication of these errors. Furthermore, we expect that the results of the research will provide opportunities in the future for remotely sensing air-sea interaction processes using hyperspectral optical techniques.

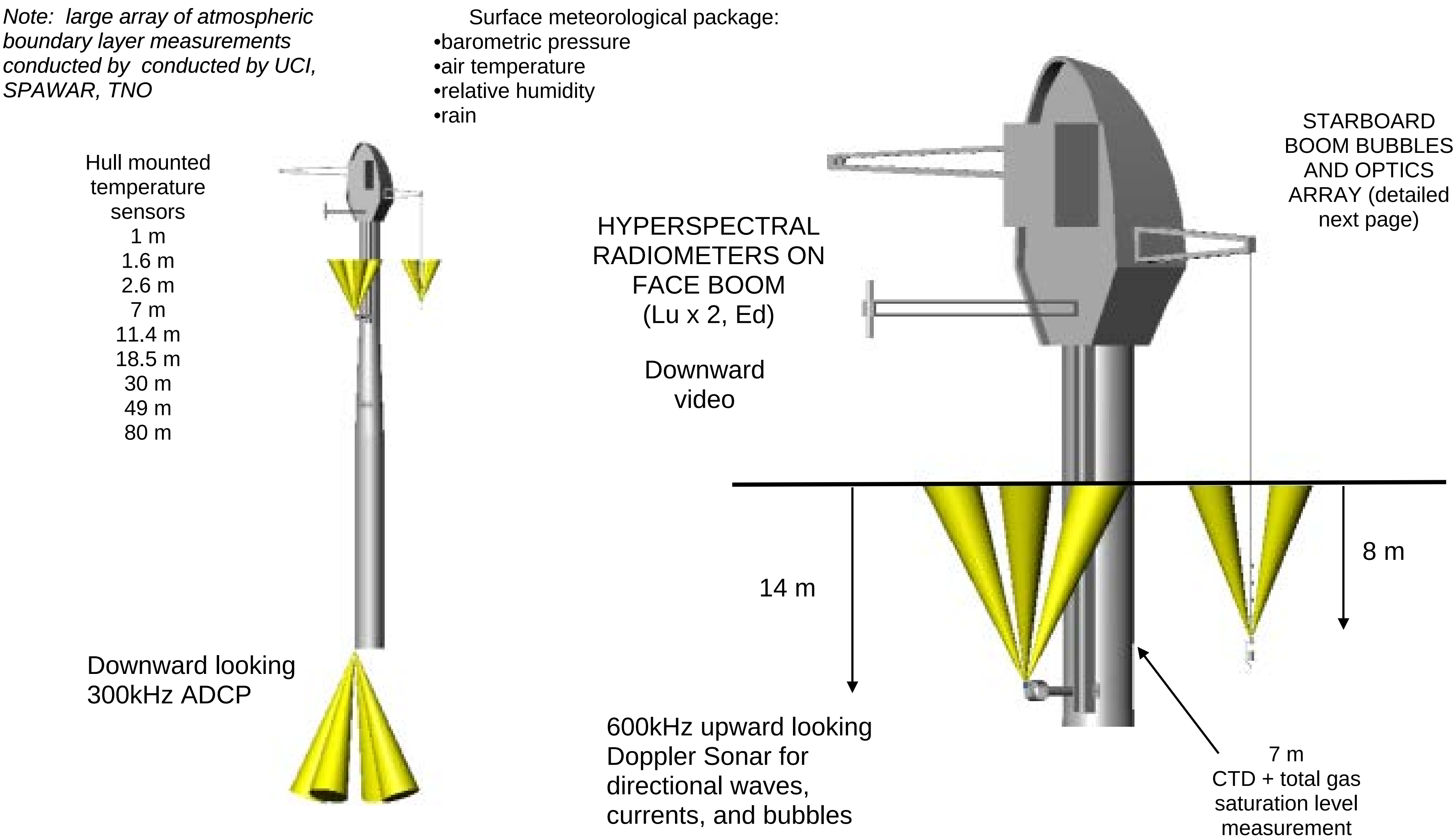
TRANSITIONS

With the two intensive field years now behind us, our group is now entering the data analysis and modeling phase of this program. A comprehensive 3-D, Monte-Carlo radiative transfer model that can arbitrary spatial distributions of bubbles or other spatial distributions of IOPs is currently being refined and will be compared with results of the conventional slab-type models as well as the reflectance measurements obtained during the 2001 field effort. Opportunities to "piggy-back" hyperspectral radiometric measurements with future air-sea interaction field studies that use either aircraft and/or FLIP will be explored. This includes the use of hyperspectral imagers such as the NRL Phills and/or STI's LASH hyperspectral imager.

PUBLICATIONS IN DIRECT RESPONSE TO THIS PROGRAM

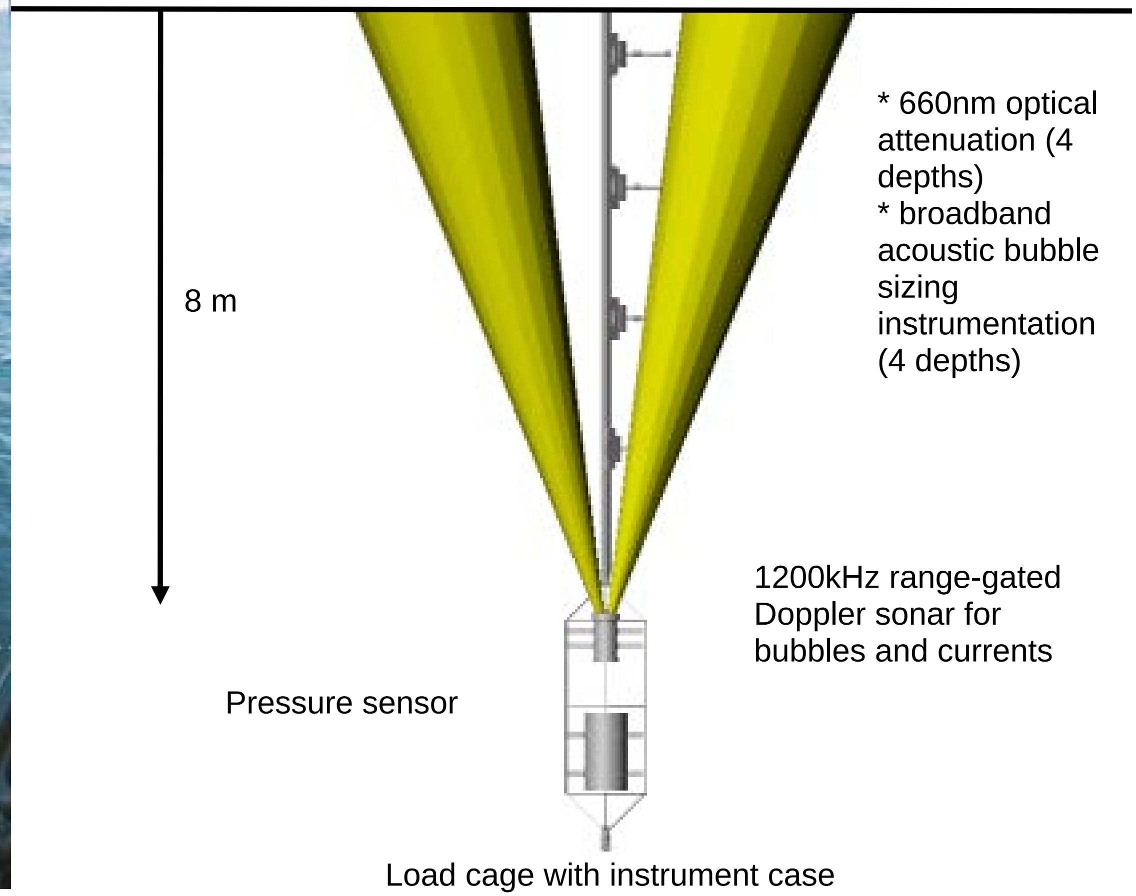
Terrill, E.J., W.K. Melville, and Stramski, D. 2001 Bubble Entrainment by Breaking Waves and their Influence on Optical Scattering in the Upper Ocean. J. Geophys. Research. 16,815 - 16,823.

Terrill, E.J., W.K. Melville, and Stramski, D. 1998. Bubble Entrainment by Breaking waves and their Effects on the Inherent Optical Properties of the Upper Ocean. SPIE Ocean Optics OOXIV, Kona, HI. November 1998.



Note: large array of atmospheric boundary layer measurements conducted by conducted by UCI, SPAWAR, TNO
Surface meteorological package:
•barometric pressure
•air temperature
•relative humidity
•rain
Hull mounted temperature sensors
1 m
1.6 m
2.6 m
7 m
11.4 m
18.5 m
30 m
49 m
80 m
Downward looking 300kHz ADCP
HYPERSPECTRAL RADIOMETERS ON FACE BOOM (Lu x 2, Ed)
Downward video
STARBOARD BOOM BUBBLES AND OPTICS ARRAY (detailed next page)
14 m
8 m
600kHz upward looking Doppler Sonar for directional waves, currents, and bubbles
7 m CTD + total gas saturation level measurement

STARBOARD BOOM BUBBLES AND OPTICS
ARRAY



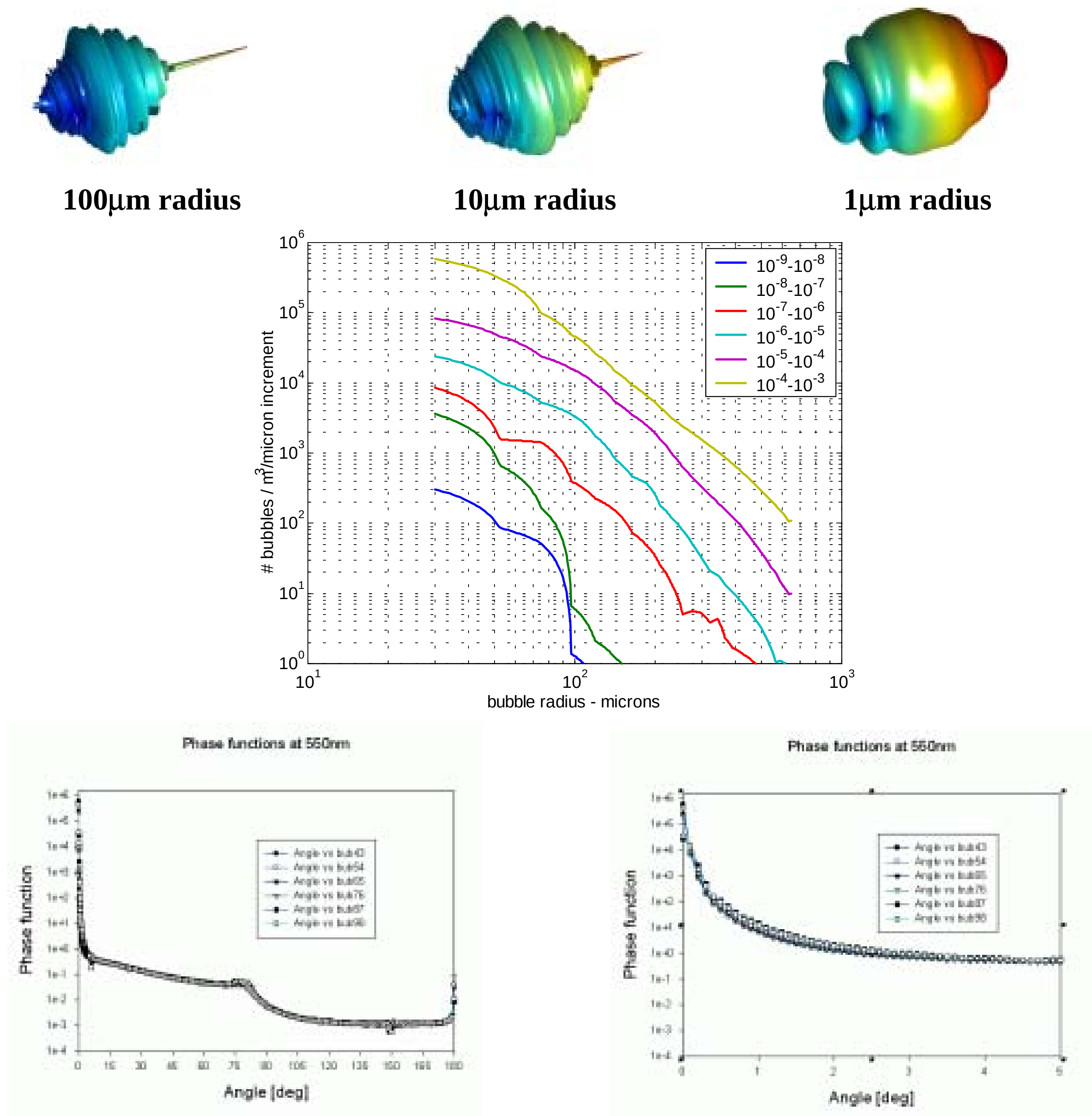


Figure 3. Top. Phase function calculations at 550nm for 3 different bubble sizes shown below. Distance from origin is proportional to the logarithm of the intensity of scattered light. Color represents distance from the origin. The computations shown the very strong forward scattering that occurs with light scattering from individual bubbles. Middle. Bubble size distributions measured in the field and binned according to their void fraction spanning 6 orders of magnitude of bubble densities. Bottom left. Phase functions for the various average size distributions shown computed using Mie theory. Bottom right. Zoomed in figure of the bubble population phase functions over the range of 0-5 degrees. The computations indicate that while the shape of the bubble size distributions evolve, the phase functions are relatively stable for the bubble populations expected in the upper ocean. A computation of the phase functions is a necessary input for conducting the planned radiative transfer modeling which will include the effects of the bubbles. The sharp forward scattering of the bubble population phase functions also indicates the difficulty in performing scattering measurements within bubble populations since the majority of the scatter occurs in the first degree.

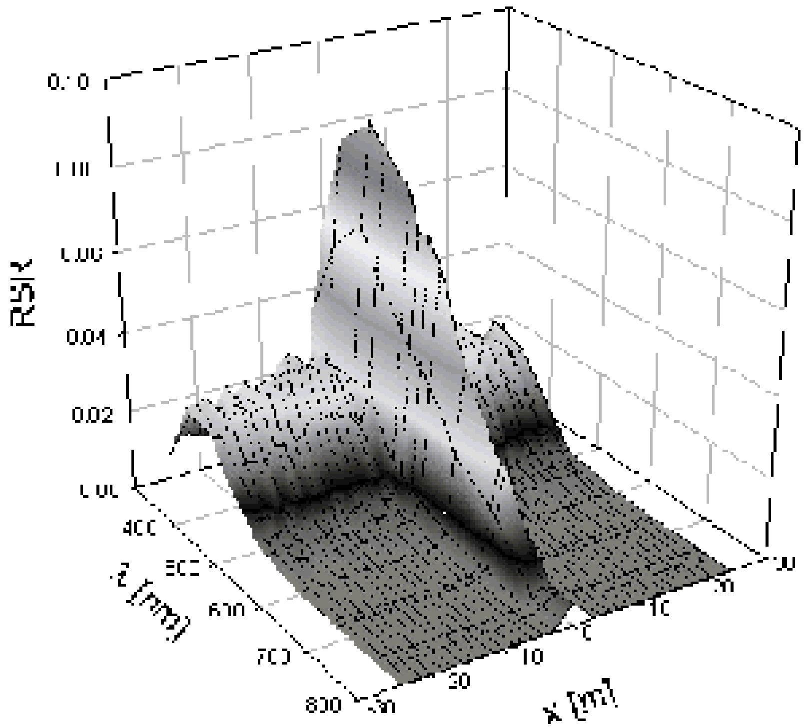


Fig. 4. Results of 3-D Monte Carlo simulations of the spectral remote-sensing reflectance over a bubble cloud (the x-axis represents a cross section across the bubble cloud center). Note the non - zero reflectance in the red that results from the presence of bubbles near the ocean's surface.